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Author list: W. B. Colson

Author affiliation: Physics Department,
Naval Postgraduate School, Monterey, CA 93943 USA

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Corresponding author name: W. B. Colson

Email address: Colson@nps.navy.mil

Postal address: Physics Department,
Naval Postgraduate School, Monterey, CA 93943 USA

Phone Number: 831-656-2765

Fax Number: 831-656-2765

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W. B. Colson

Physics Department, Naval Postgraduate School, Monterey CA 93943 USA

ABSTRACT

Twenty-four years after the first operation of the short wavelength free electron laser (FEL) at Stanford University, there continue to be many important experiments, proposed experiments, and user facilities around the world. Properties of FELs operating in the infrared, visible, UV, and x-ray wavelength regimes are listed and discussed.

The following table lists existing and proposed relativistic free electron lasers (FELs) in 2001. The top part of the table lists existing FELs, and the bottom part of the table lists proposed FELs. Each FEL is identified by a location, or institution, followed by the FEL's name in parentheses. The table can be found at

<http://www.physics.nps.navy.mil/fel.html>.

Additions and corrections can be transmitted to us for inclusion on the table in the future.

The first column of the table lists the operating wavelength λ , or wavelength range. The large range of operating wavelengths, six orders of magnitude, indicates the flexible design characteristics of the FEL mechanism. In the second column, σ_z is the electron pulse length divided by the speed of light c , and ranges from CW to short sub-picosecond pulse time scales. The expected optical pulse length can be 3 to 5 times shorter or longer than the electron pulse depending the optical cavity Q , the FEL desynchronization, and the FEL gain. If the FEL is in an electron storage-ring, the optical pulse is typically much shorter than the electron pulse. Most FEL oscillators produce an optical spectrum that is Fourier transform limited by the optical pulse length.

The electron beam energy E and peak current I provided by the accelerator are listed in the third and fourth columns. The accelerator type is listed as the first entry in the last column with a code such as RF for the radio-frequency linac. While there are a variety of accelerators used, most are RF with some electron storage rings, microtrons, and electrostatic accelerators. Storage rings tend to be used for the short wavelength applications, while the electrostatic accelerators provide longer wavelengths.

The next three columns list the number of undulator periods N , the undulator wavelength λ_0 , and the undulator parameter $K = eB\lambda_0/2\pi mc^2$ where e is the electron charge magnitude, B is the rms undulator field strength, and m is the electron mass. For an FEL klystron undulator, there are multiple undulator sections as listed in the N -column. Note that the range of values for N , λ_0 , and K are much smaller than for the other parameters indicating that most undulators are similar. Only a

few of the FELs use the klystron undulator at present, and the rest use the conventional periodic undulator. The FEL resonance condition,

$$\lambda = \frac{\lambda_0(1 + K^2)}{2\gamma^2} ,$$

where γ is the relativistic Lorentz factor $\gamma = E/mc^2$, provides a relationship that can be used to derive K from λ , E , and λ_0 . The middle entry of the last column lists the FEL type: "O" for oscillator, "A" for amplifier, etc. Most of the FELs are oscillators, but recent progress has resulted in short wavelength FELs using SASE (Stimulated Amplification of Spontaneous Emission) to produce 109nm radiation. A reference describing the FEL is provided at the end of each line entry.

For the conventional undulator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator spectral bandwidth, $1/4N$, or $P \approx EI/4eN$. For the FEL using a storage ring, the optical power causing saturation is substantially less than this estimate and depends on ring properties. For the high-gain FEL amplifier, the optical power at saturation can be substantially more. The average FEL power is determined by the duty cycle, or spacing between electron pulses, and is typically many orders of magnitude lower than the peak power. The TJNAF IR FEL has now reached an average power of 2 kW with the recovery of the electron beam energy in superconducting accelerator cavities.

In the FEL oscillator, the optical mode that best couples to the electron beam in an undulator of length $L = N\lambda_0$ has Rayleigh length $z_0 \approx L/12^{1/2}$ and has a mode waist radius of $w_0 \approx N^{1/2}\gamma\lambda/\pi$. The FEL optical mode typically has more than 90% of the power in the fundamental mode described by these parameters.

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Relativistic Short Wavelength Free Electron Lasers (2001)

FELs	λ (μm)	σ_z	E(MeV)	I(A)	N	λ_0 (cm)	K(rms)	Acc., Type[Ref.]
EXISTING =====								
UCSB(mm FEL)	340	25 μs	6	2	42	7.1	0.7	EA,O[1]
Dartmouth(FEL)	200	CW	0.04	0.001	50	300	-	SP,O[2]
KAERI(FIR-FEL)	97-150	25ps	6.5	0.5	80	2.5	1.6	MA,O[47]
Himeji(LEENA)	65-75	10ps	5.4	10	50	1.6	0.5	RF,O[3]
UCSB(FIR FEL)	60	25 μs	6	2	150	2	0.1	EA,O[1]
Osaka(ILC/ILT)	47	3ps	8	50	50	2	0.5	RF,O[4]
Osaka(ISIR)	40	30ps	17	50	32	6	1	RF,O[5]
Tokai(JAERI-FEL)	15-22	5ps	16.5	100	52	3.3	0.7	RF,O[6]
Bruyeres(ELSA)	20	30ps	18	100	30	3	0.8	RF,O[7]
Osaka(iFEL4)	18-40	10ps	33	40	30	8	1.3-1.7	RF,O[8]
UCLA-Kurchatov	16	3ps	13.5	80	40	1.5	1	RF,A[9]
LANL(RAFEL)	15.5	15ps	17	300	200	2	0.9	RF,O[10]
Stanford(FIREFLY)	15-75	1-5ps	15-32	14	25	6	1	RF,O[11]
UCLA-Kurchatov-LANL	12	5ps	18	170	100	2	0.7	RF,A[12]
Maryland(MIRFEL)	12-21	5ps	9-14	100	73	1.4	0.2	RF,O[13]
Beijing(BFEL)	5-20	4ps	30	15-20	50	3	1	RF,O[14]
Darmstadt(IR-FEL)	6-8	2ps	25-50	2.7	80	3.2	1	RF,O[15]
BNL(HGHG)	5.3	6ps	40	120	60	3.3	1.44	RF,A[16]
Osaka(iFEL1)	5.5	10ps	33.2	42	58	3.4	1	RF,O[17]
Tokyo(FEL-SUT)	4-16	2ps	32-40	0.2	43	3.2	0.7-1.8	RF,O[48]
Nieuwegein(FELIX)	3-250	1ps	50	50	38	6.5	1.8	RF,O[18]
Duke(MarkIII)	3	3ps	44	20	47	2.3	1	RF,O[19]
TJNAF(FEL)	1-6	0.4ps	48	60	41	2.7	0.9	RF,O[20]
Stanford(SCAFEL)	3-13	.5-12ps	22-45	10	72	3.1	0.8	RF,O[21]
Orsay(CLIO)	3-53	0.1-3ps	21-50	80	38	5	1.4	RF,O[22]
Vanderbilt(FELI)	2.0-9.8	0.7ps	43	50	52	2.3	1	RF,O[23]
Osaka(iFEL2)	1.88	10ps	68	42	78	3.8	1	RF,O[17]
Nihon(LEBRA)	1.5	10ps	86.8	5	50	4.8	0.92	RF,O[49]
BNL(VISA)	0.8	2ps	70.9	250	220	1.8	1.2	RF,S[50]
BNL(ATF)	0.6	6ps	50	100	70	0.88	0.4	RF,O[24]
Dortmund(FELICITAI)	0.42	50ps	450	90	17	25	2	SR,O[25]
ANL(APSFEL)	0.385	0.65ps	354	184	648	3.3	2.2	RF,S[40]
Orsay(Super-ACO)	0.3-0.6	15ps	800	0.1	2x10	13	4.5	SR,O[26]
Osaka(iFEL3)	0.3-0.7	5ps	155	60	67	4	1.4	RF,O[27]
Okazaki(UVSOR)	0.2-0.6	6ps	607	10	2x9	11	2	SR,O[28]
Tsukuba(NIJI-IV)	0.2-0.6	160ps	310	5	2x42	7.2	2	SR,O[29]
Duke(OK-4)	0.2-0.7	1.6ps	850	35	2x33	10	0-4	SR,O[30]
Italy(ELETTRA)	0.2-0.4	28	1000	150	2x19	10	4.2	SR,O[38]
DESY(TTF1)	0.109	0.5ps	233	300	492	2.73	0.81	RF,S[42]
PROPOSED =====								
Florida(CREOL)	355	8 μs	1.3	0.13	185	0.8	0.1	EA,O[31]
Netherlands(TEUFEL)	180	20ps	6	350	50	2.5	1	RF,O[32]
Rutgers(IRFEL)	140	25ps	38	1.4	50	20	1	MA,O[33]
Moscow(Lebedev)	100	20ps	30	0.25	35	3.2	0.8	MA,O[34]
Novosibirsk(RTM)	2-11	20ps	98	100	4x36	9	1.6	RF,O[35]
TJNAF(UVFEL)	0.16-1	0.2ps	160	270	72	3.3	1.3	RF,O[20]
Rocketyne/Hawaii(FEL)	0.3-3	2ps	100	500	84	2.4	1.2	RF,O[36]
Harima(SUBARU)	0.2-10	26ps	1500	50	33,65	16,32	8	SR,O[37]
ANL(APSFEL)	0.12	1ps	440	150	864	3.3	3.1	RF,S[40]
BNL(DUVFEL)	0.1	6ps	230	1000	256	2.89	1.2	RF,A[39]
Frascati(COSA)	0.08	10ps	215	200	400	1.4	1	RF,O[41]
Duke(VUV)	0.01-1	1ps	1000	50	4x32	12	3	SR,O[43]
DESY(TTF2)	0.006	0.17ps	1000	2500	981	2.73	0.9	RF,S[44]
BESSY(FEL)	0.0012	0.08ps	2250	5000	1450	2.75	0.85	RF,S[51]
SLAC(LCLS)	0.00015	0.07ps	14350	3400	3328	3	3.7	RF,S[45]
DESY(TESLA)	0.0001	0.08ps	30000	5000	4500	6	3.2	RF,S[46]
DRESDEN(ELBE1)	3-30	0.5-1ps	10-40	30-60	2x34	2.73	0.3-0.8	RF,O[52]
DRESDEN(ELBE2)	30-100	1ps	10-40	30	45	5	0.4-1.6	RF,O[52]
Novosibirsk(RTM1)	100-200	100ps	14	20-100	2x36	12	1.2	RF,O[53]

RF - RF Linac Accelerator
 SR - Electron Storage Ring
 A - FEL Amplifier
 SP - Smith-Purcell Oscillator

MA - Microtron Accelerator
 EA - Electrostatic Accelerator
 O - FEL Oscillator
 S - SASE FEL

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